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13. ABSTRACT *(Maximum 200 words)*

SAA International, under contract to Southern Ballistics, Inc., undertook a development project to greatly improve the performance of armor piercing ammunition fired from the .50 caliber M2 heavy barrel machinegun. This brief presentation will highlight the projectile design approach, the resulting armor penetration performance, and the significant contribution of Bofors' double-base, single perforation propellant, which permitted us to realize our muzzle velocity objectives, within the safe pressure limits of the weapon.

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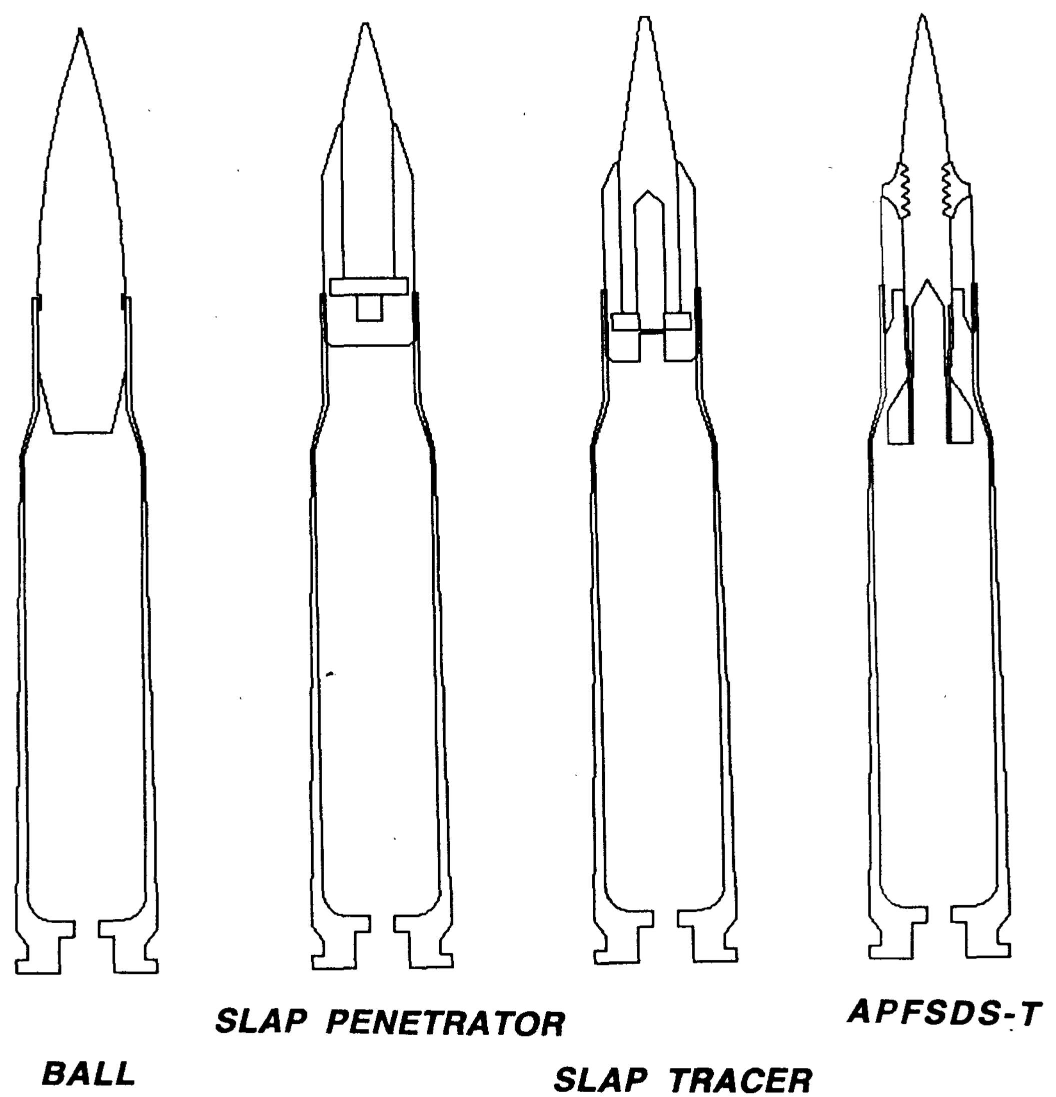
1. Title Sheet

SAA International, under contract to Southern Ballistics, Inc., undertook a development project to greatly improve the performance of armor piercing ammunition fired from the .50 caliber M2 heavy barrel machinegun. This brief presentation will highlight the projectile design approach, the resulting armor penetration performance, and the significant contribution of Bofors' double-base, single perforation propellant, which permitted us to realize our muzzle velocity objectives, within the safe pressure limits of the weapon.

.50 CALIBER AP CARTRIDGE TECHNOLOGY



2. AP Cartridge Technology

.50 caliber armor piercing ball-type technology begins in the 1920's and evolves over the next 70 years into a wide range of hardened steel core, tungsten carbide, and explosive filled projectiles all within the same basic aerodynamic shaped and weight (50 to 60 grams). Muzzle velocity is relatively low (about 2800 fps), but the mass-velocity relationship provides adequate terminal effects against lightly armored targets out to about 500 yards. Soft targets (people), provided they are not moving, can usually be hit out to 800 yards (1200 yards for snipers), but under these circumstances, the .50 caliber rifle provides little advantage over a .30 caliber weapon, and at a much greater weight penalty.

In the late 1970's, perhaps 25 years after the ball-type AP round became obsolete, new life was given to .50 caliber weapons with the beginning of the SLAP program (7.62 SLAP as well), at the insistence of the Marine Corps. They realized that the .50 caliber was never going to be replaced with a larger weapon or one with greater chamber volume (which is the most serious short coming since the bullet is very heavy and the available propellant volume is very small). This lack of interest in replacing the M2 results from the great expense of retrofitting thousands of tanks, APCs, and all the infantry and Marine units. It is more cost effective to develop better ammunition in the short run, and the Marines wanted a cartridge that was worth its weight.

The SLAP penetrator and SLAP tracer ammunition system represents a good first generation discarding sabot concept. Lighter overall weight (27 grams), higher muzzle velocity (4050 fps), a dense, hard tungsten alloy flight projectile with an improved ballistic coefficient for acceptable lethality out to 1500 yards. The SLAP tracer projectile is provided as well, since if you have ever fired .50 caliber without tracer rounds, you have no idea where the bullets are going. Unless you hit the ground in front of the target and walk the fire into it, firing non-tracer .50 cal is worthless. However, the SLAP tracer, due to stability requirement must sacrifice armor penetration capability. Given what was known about discarding sabot design in the 1970's and 80's, the SLAP system was a good round for the times. It is unfortunate that it has taken so long to get it into the field.

Since then, sabot design has evolved. We can now analyze the SLAP sabot and determine that it has a fundamental structural flaw that manifests itself in occasional in-bore failures, poor sabot separation, and resulting inaccuracies. These shortcomings also apply to the 7.62 SLAP since it is based on the same design concept.

The source of the problem is the plastic cup sabot which is notched forward of the pusher plate. The idea is that these notches will result in the sabot opening up into four fingers and release the flight projectile upon muzzle exit. Unfortunately, if you really think about how this sabot is intended to function, there is a contradiction. In the bore, the sabot fingers are supposed to resist the rotational forces and firmly hold the penetrator so that it does not wobble and break free, causing catastrophic damage to the barrel. However, these same rotational forces are then supposed to break the sabot so that it can cleanly separate upon muzzle exit. Well the rotational forces are a maximum at the muzzle. Therefore, for this sabot to work flawlessly, it must fracture exactly at the muzzle every time. Unfortunately, this is an impossibility, given all the variables involved.

What occurs when one observes poor sabot separation is that the sabot was too strong and did not fracture at the muzzle and is then violently stripped by ram air pressure, which sends the projectile on an erratic flight.

When there is a catastrophic in-bore failure, the sabot was marginally too weak and fractured too soon in the barrel, completely releasing the penetrator.

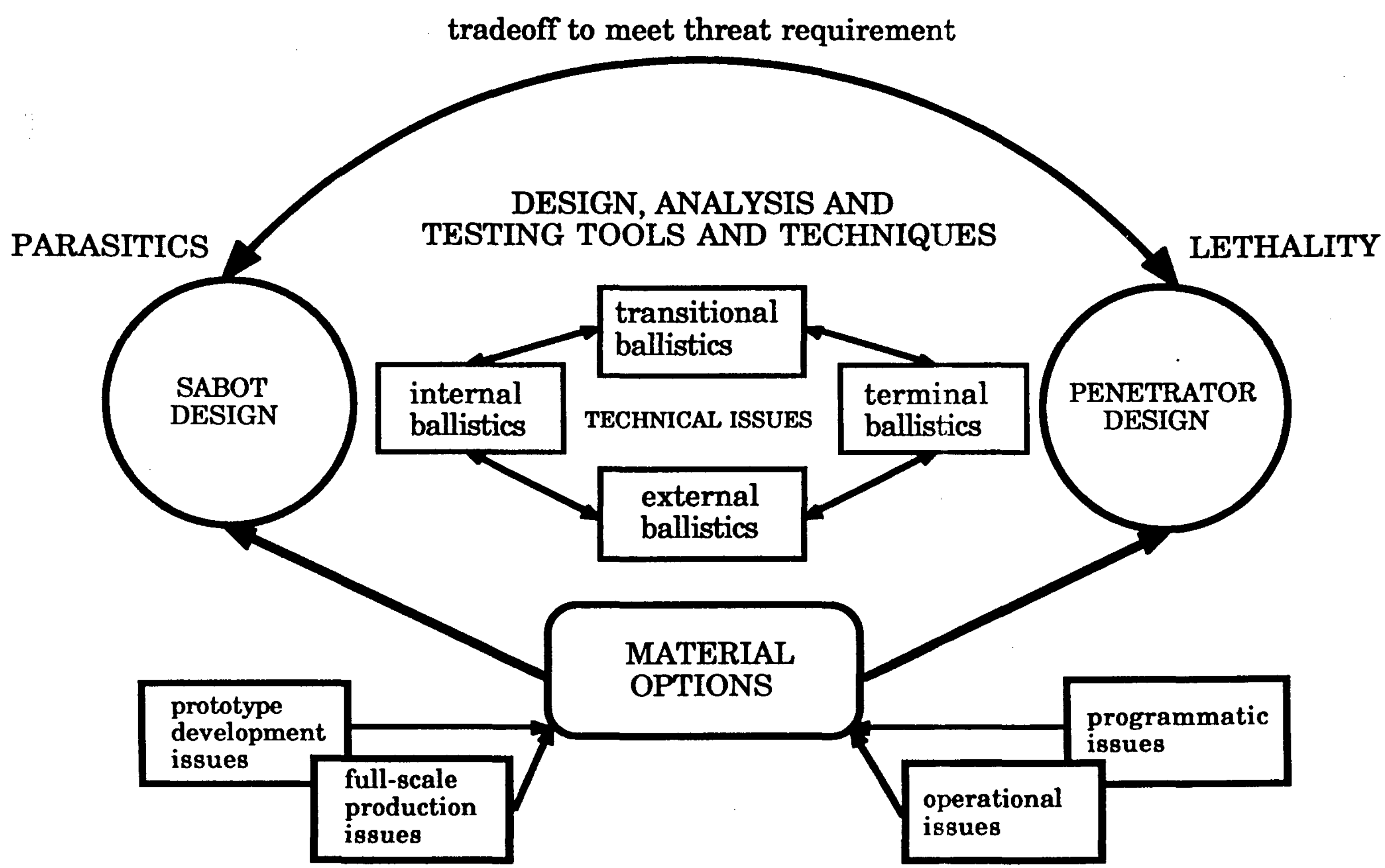
When the round appears to perform acceptably, the sabot has still failed in-bore. However, this failure has occurred a few inches from the muzzle and the penetrator has not had enough time to move in a catastrophic manner before the round exists. This is why the round appears to work most of the time. The sabot has been tuned, at great expense, to fail just prior to muzzle exit. By today's standards, however, this is an unacceptable design practice.

Armed with this knowledge, SAA accomplished two things: 1) we designed and tested an

acceptable cup sabot concept which could use the existing SLAP penetrator and tracer subprojectiles and realize proper and reliable sabot separation, without any mechanical contradictions. However, we also put the two projectiles together into the fin stabilized design shown here, which has succeeded in furthering the state-of-the-art, and became the selected design candidate.

What we have done is to place the plastic obturator behind a segmented, structural aluminum sabot. In this manner, plastic components are held in hydrostatic compression by the propellant pressure, while they provide in-bore stability. This is a good function for plastic materials. Plastics have very poor strength characteristics, especially in tension. Therefore, they should be used under conditions of compression, where their strength can be exceeded but the material cannot flow or break free. Upon muzzle exit, the confining pressure is released and the plastic rebounds and is assisted in separating from the projectile by the confined gas pressure. With such a design, structural components play unique, non-conflicting mechanical roles. The result is safe and reliable in-bore integrity as well as sabot separation. The resulting trajectory accuracy has proved exceptional, as tested.

K.E. PROJECTILE BEST FEASIBLE SOLUTION RESULTS FROM AN ITERATIVE SYSTEMS ANALYSIS PROCESS

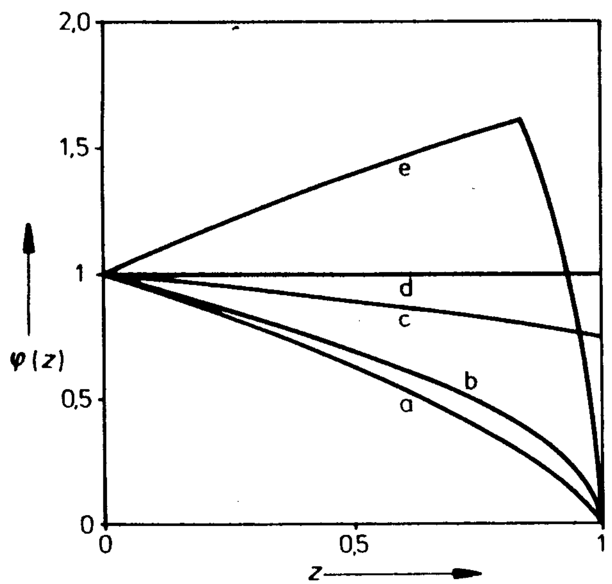


3. Iterative Systems Analysis Process

Very briefly, these are some of the two dozen issues the engineer juggles in his mind as the design converges. The four ballistic issues in the middle are iterated to reach the final configuration. It really does not matter where you jump on the track, you are going to go around it many times. We did thirty design iterations with six testing cycles.

As the title of this figure states, we were looking for a "best feasible solution," as opposed to an optimum design, since we were constrained by both time and money. This is an NDI design and we did not have many years to play with it. Once we had a configuration which worked well enough we considered it complete. This is the most economical way to rapidly apply improved technology and get it to the field where it is most needed.

GRAIN FORM FUNCTION
(BURNING SURFACE AS A FUNCTION OF BURNING THICKNESS)



a = Cubical or spherical propellant

b = Solid cylinder propellant

c = Strip propellant ($\delta = 1/10$)[1]

d = Tubular propellant

e = Seven hole propellant ($D_c = 10 d_c$)[2]

---

1) δ = Thickness/width of the strip $\ll 1/4$

2) D_c = the outside diameter of the propellant rod,
d_c = the diameter of the perforations

4. Grain Form Function

Now I can talk about the great things Bofors did for us. This graph shows the change in a propellant grain's burning surface as the grain burns through its thickness, for several grain geometries. Typical small arms propellant grains are spherical, solid cylinder, or strip propellant (items a to c). Item a being the most common U.S. military small arms propellant -- ball powder. Since these three geometries show a downward trend as they burn, they are termed "regressive," meaning they will generate gas pressure at a slower rate for the same chamber pressure.

Item d, tubular or single-perf propellant, is flat over its thickness and is termed a "neutral" grain. Its geometry does not affect the acceleration of the grain burning rate as the chamber pressure increases.

Item e is "progressive", since the grain surface increases as the grain is consumed. This grain causes an acceleration of the burning rate as chamber pressure increases.

Bofors has applied single-perf to systems from 5.56 through 40mm. 7 and 19 perf grains exist, which are even more progressive, but in order to get all these holes in the grain, the grains begin to get large and packaging these propellant is restricted to larger caliber guns.

So what does all this mean about getting high muzzle velocity with lighter projectiles?

Well, if you imaging that as the propellant begins to burn, a little bit of pressure develops. This pressure pushes the bullet slightly forward. Suddenly, the chamber volume is a little larger. The propellant now has to burn faster to maintain or increase the pressure behind the projectile. The cycle continues with the projectile out running the pressure and the pressure running to catch up.

Now with relatively heavy projectiles, like the ball round, a regressive grain is acceptable because the projectile is harder to get started down the barrel. The propellant will burn faster and evolve gas pressure faster based only on an increasing chamber pressure. You have to remember that

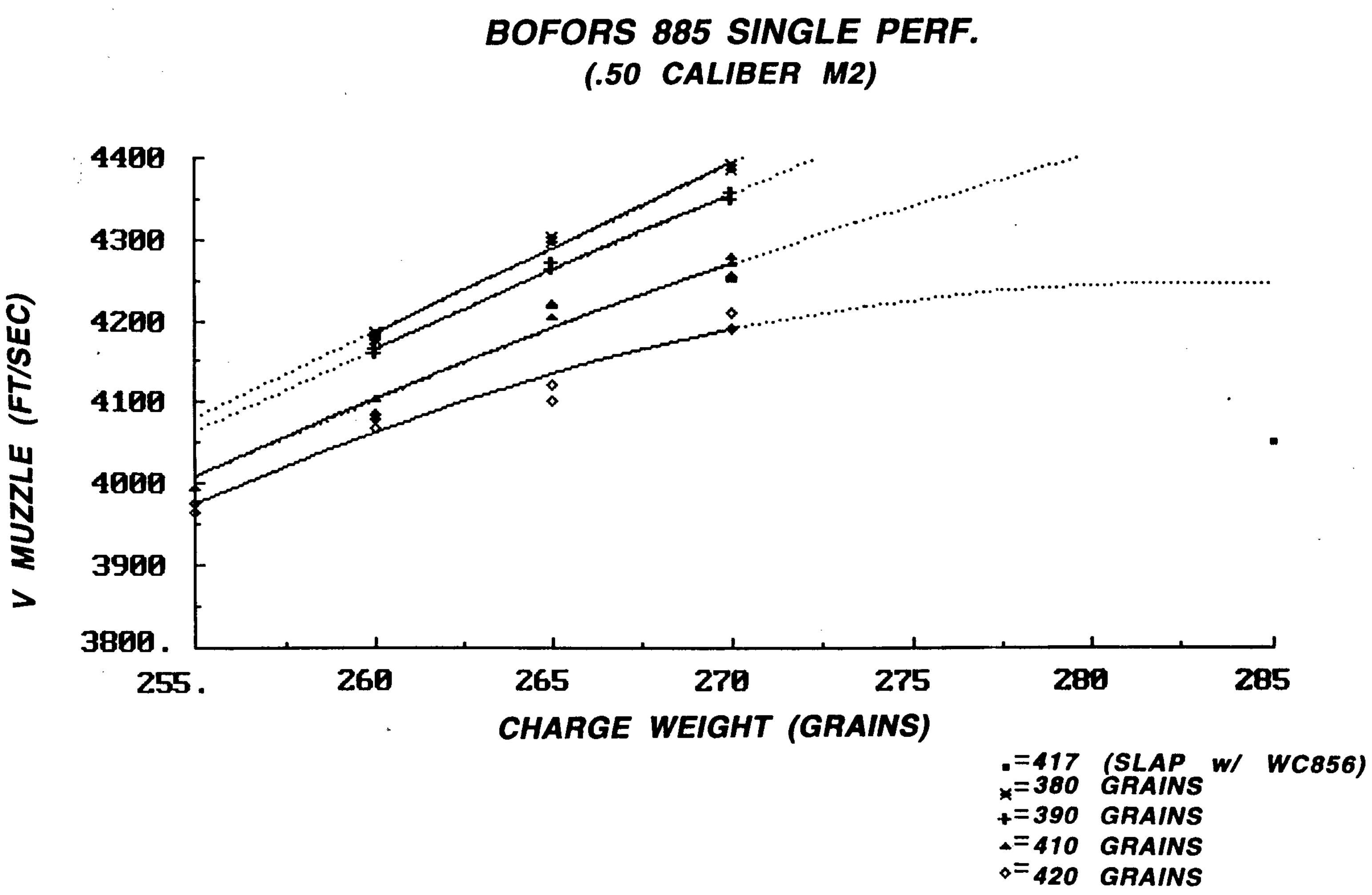
burning rate is a function of both chamber pressure and burning surface. For heavy projectiles, the chamber pressure will increase despite the regressive characteristics of the grain. However, if one uses a regressive grain designed for a heavy projectile now with a lighter projectile, the maximum pressure will be lower, as will the muzzle velocity.

O.K, you're convinced maybe that we need a more progressive grain. Well then why does the current SLAP use a ball powder? It works.

The answer is that a ball powder can be made to burn less regressively by adding burning rate deterrents to the outer surface. In fact the grain is stratified. Ball powder is double- base, but when the nitroglycerine is absorbed into the nitrocellulose it occurs in an uneven manner through the thickness. Therefore, it will show many different burning characteristics over time. In addition, burning rate deterrents can be added in various amounts through the thickness. The result is that the geometry can be fooled and the grain burnt more progressively by slowing down the initial consumption of the propellant ball, but speeding it up later on.

The use of deterrents, however, are not without their penalty. Deterrents are less energetic plasticizers. In other words, the use of deterrents reduces the overall energy density of the propellant. As a result, a deterred ball powder, by weight, is less energetic than an undeterred single-perf, even though both grains may burn neutral. Less energy in the cartridge gives less muzzle velocity, and this is what we found in testing.

Ball powder manufacturers, to make up for the lower energy density due to the use of deterrents, add much more nitroglycerine to the formula. However, this practice results in unsafe long term storage characteristics, which will be discussed shortly.

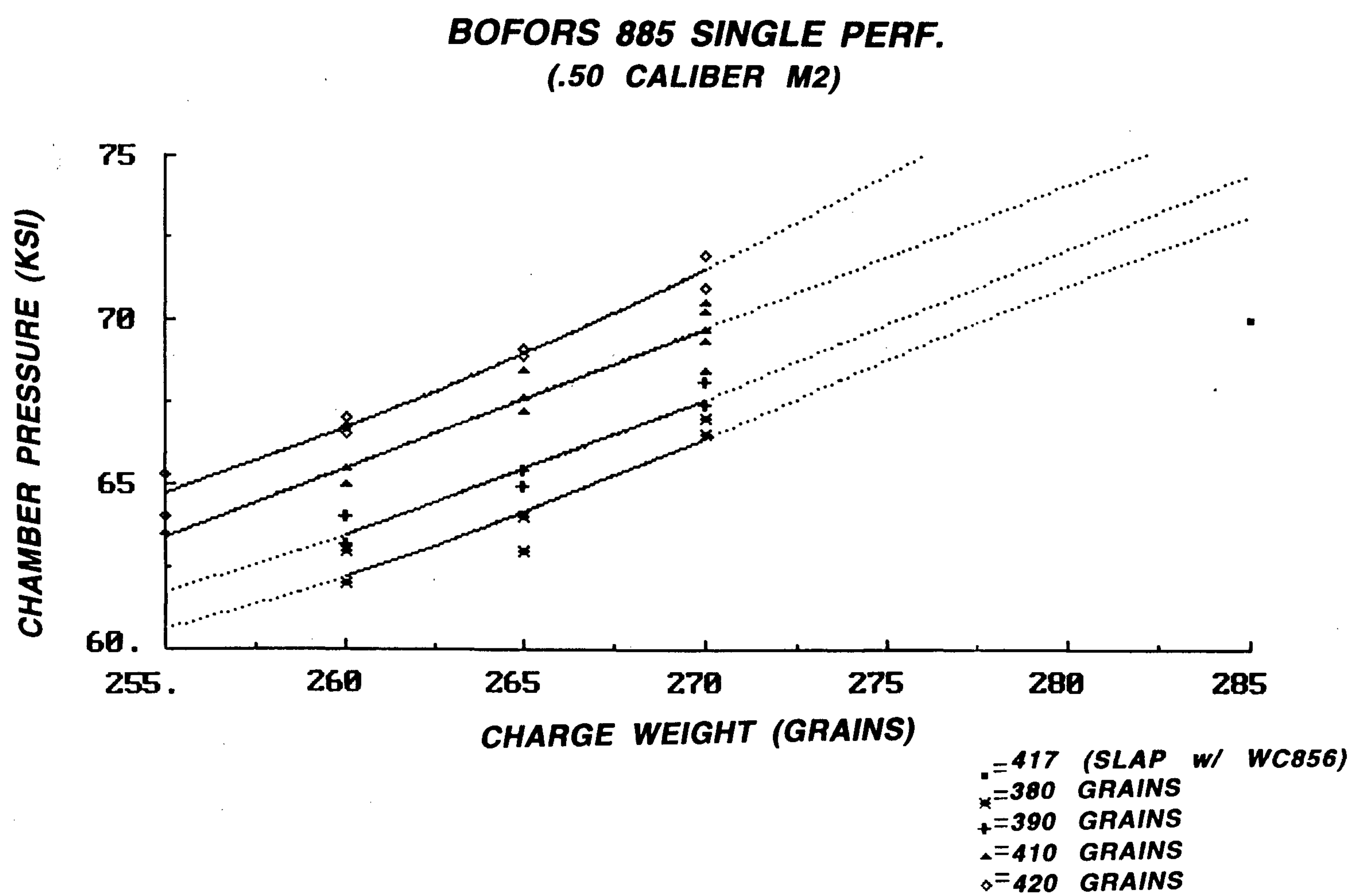


BOFORS 885 SINGLE PERF.
(.50 CALIBER M2)
V MUZZLE (FT/SEC)
4400
4300
4200
4100
4000
3900
3800.
255.
260
265
270
275
280
285
CHARGE WEIGHT (GRAINS)
■=417 (SLAP w/ WC856)
✱=380 GRAINS
+=390 GRAINS
▲=410 GRAINS
◇=420 GRAINS

5. Muzzle Velocity versus Charge Weight

As part of the propellant subsystem tradeoff, we developed test data using a number of charge weights and different projectile weights. This allows us to select the best combination for the design during the iterative process. For reference, the SLAP cartridge is the little dot on the far right at 285 grains of WC856 propellant. Even with a slightly heavier test projectile, the Bofors single perf provides a higher muzzle velocity with only 260 grains of propellant. At 270 grains, the lightest projectile sees an impressive 4400 fps at the muzzle. Since the upward trends in the data begin to show diminishing returns, there is indication that even greater muzzle velocity can be achieved by optimizing the Bofors grain geometry to this cartridge configuration and by using more than 270 grains of propellant. At present, however, we found the off-the-shelf propellant to be satisfactory to our needs.

The final design weighs 410 grains and with a propellant weight of 270 grains it exists at 4250 fps, a full 200 fps faster than the current SLAP cartridge. At the muzzle, that translates to a 10% increase in kinetic energy. Since our projectile also has a higher ballistic coefficient, at the 275 yard target we realize a 16% increase in kinetic energy. At 1500 yards, due to the greatly reduced drag, kinetic energy is well over twice that of the SLAP penetrator. Finally, this round sees the 1500 yard SLAP energy at nearly 3000 yards. As I will show shortly, these increases in terminal kinetic energy at both short and long range directly relate to increased armor penetration.



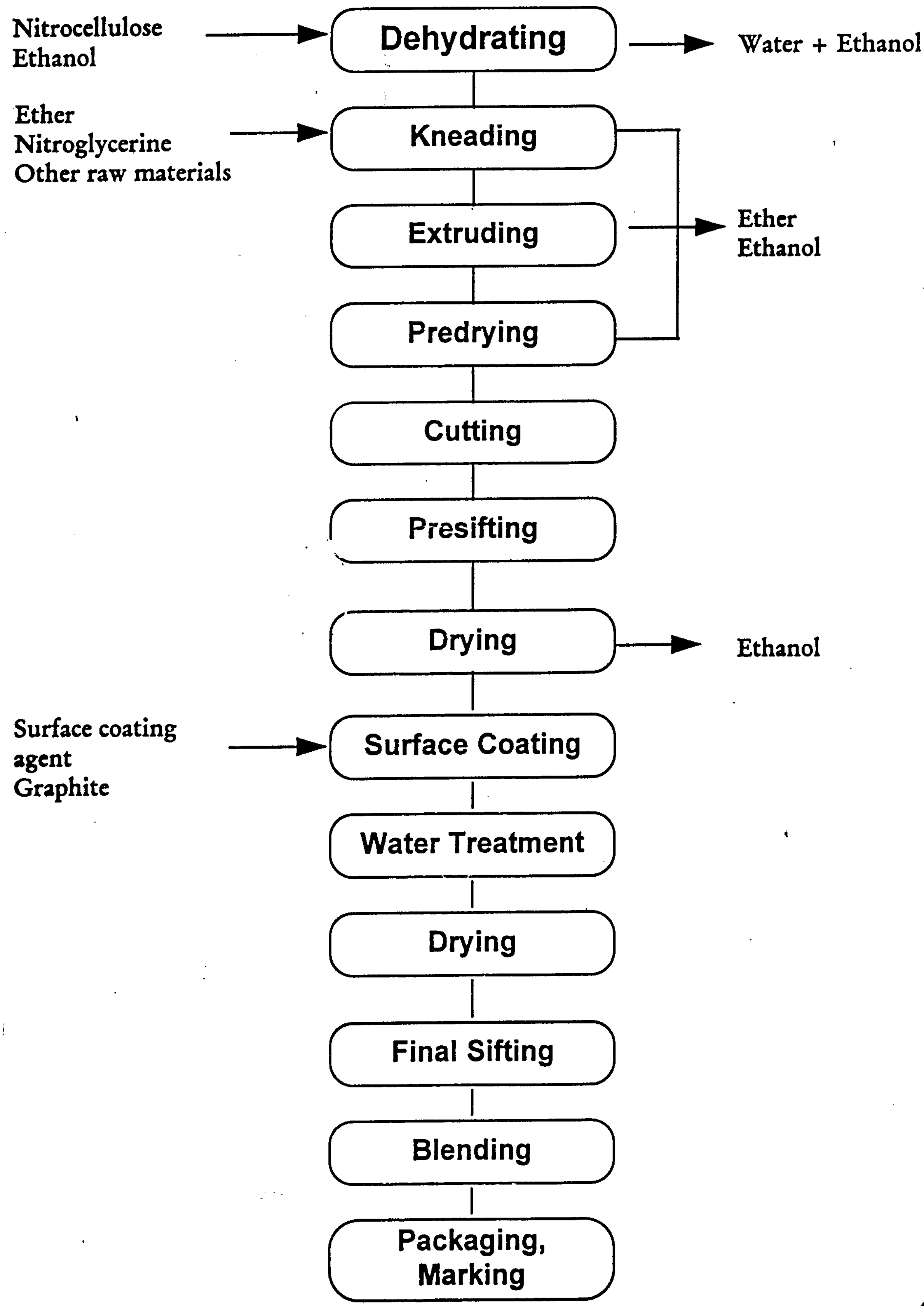
BOFORS 885 SINGLE PERF.
(.50 CALIBER M2)
CHAMBER PRESSURE (KSI)
75
70
65
60.
255.
260
265
270
275
280
285
CHARGE WEIGHT (GRAINS)
=417 (SLAP w/ WC856)
=380 GRAINS
=390 GRAINS
=410 GRAINS
=420 GRAINS

6. Chamber Pressure versus Charge Weight

We also measured peak chamber pressure for these same propellant and projectile weight combinations. For reference, the SLAP round is the little dot off to the right at 285 grains and 70 ksi pressure. Using the Bofors single perf, only the 420 grain projectile with 270 grains of propellant slightly exceeded this baseline. The final design, however, at 410 grains, meets the desired specifications on chamber pressure.

Another area where greater improvements in performance could be realized in the .50 caliber M2 is to revisit the rationale behind its pressure limit specifications. These specs are as old as the ball round; were revised in the 1950's, but really only apply to the heavy ball rounds which are much more high temperature sensitive. Propellants burn more rapidly when fired at elevated temperatures, such as 145 degrees F. With a heavy projectile, the chamber pressure will rise very rapidly and upwards of 20,000 psi increases can occur. With current propellant technology and lighter weight sabot projectiles, temperature sensitivity is reduced since the lighter projectile will out run an increased burning rate. This barrel should, therefore, be allowed to operate in the 75 ksi to 80 ksi region, which would further increase its armor penetration performance regardless of the sabot technology employed.

Manufacturing of Single- or Doublebase Propellant for Small Caliber Ammunition



BOFORS EXPLOSIVES

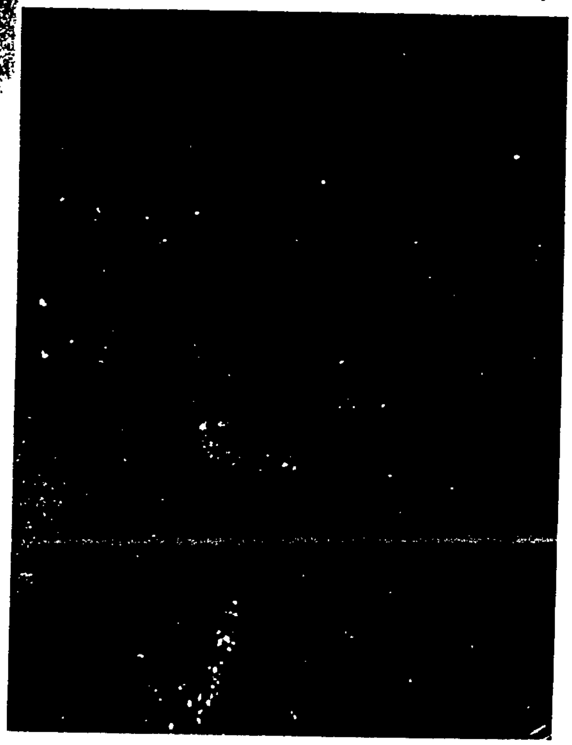
7. Propellant Manufacturing Process

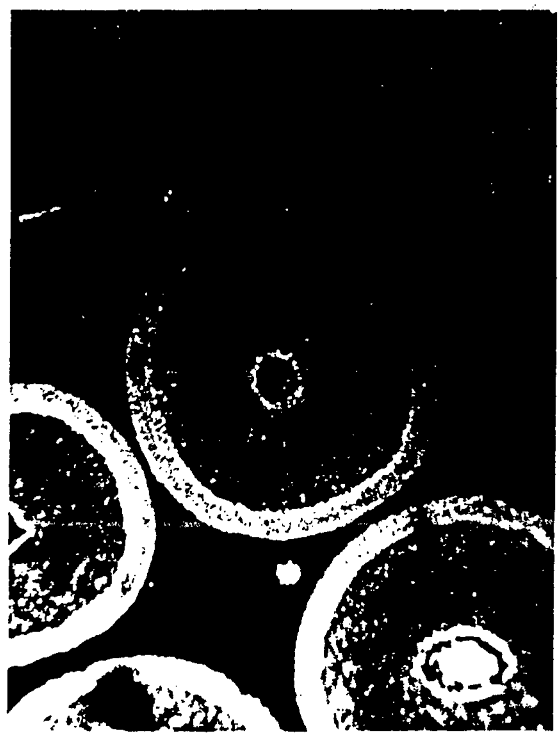
This by the way is the same Bofors propellant manufacturing process which produces the propellant used in the new .300 Win Mag cartridge discussed earlier this morning. Bofors manufactures that propellant, which is distributed in the United States by Hercules.

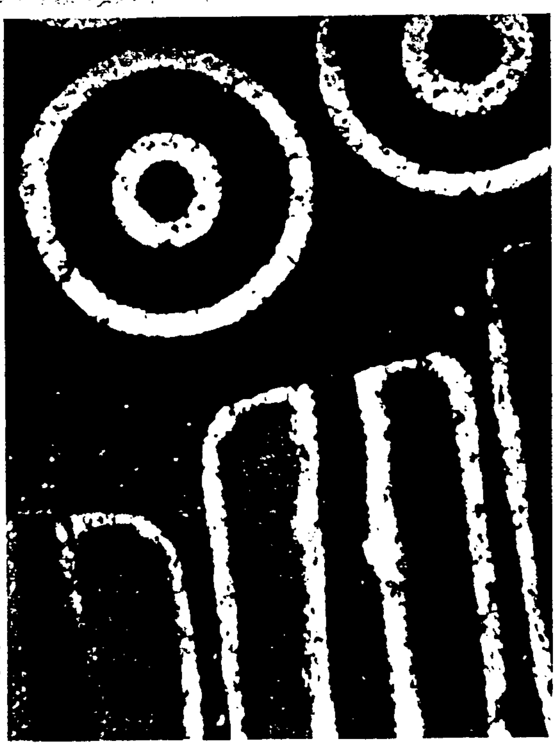
There are several unique manufacturing processes which Bofors employs when making the single perf grain, which enhance performance, reliability, and safety. Beginning with the base nitrocellulose material, approximately 12% nitroglycerine in an ether solvent is <u>evenly</u> blended during a kneading process. [This contrasts to ball powder which needs to absorb greater amounts of nitroglycerine through the surface of the ball. Surface absorption does not result in a uniform nitroglycerine intake and this has important safety implications, as will be discussed.]

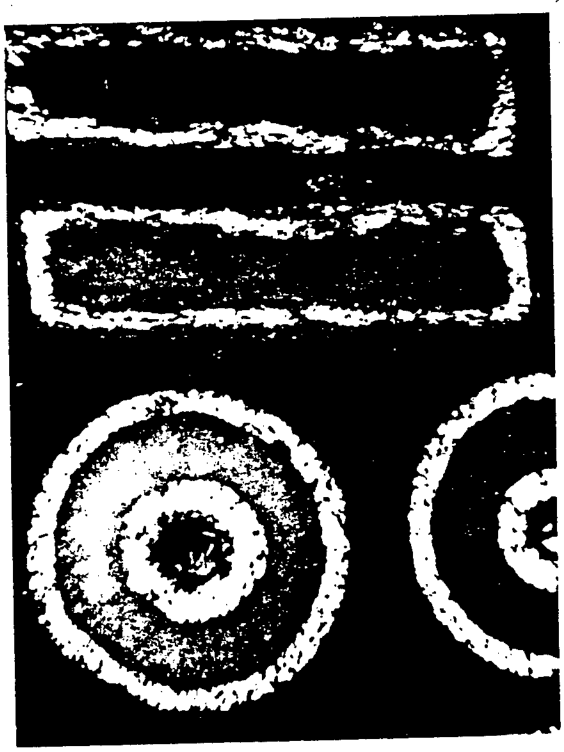
The single perf grain is then produced through extrusion at a larger size than required, since during predrying it will shrink to 65% of original size. The fact that the grain shrinks makes it more convenient to get a small hole down the middle. These grains are very small, 1.23 mm in length with a web thickness of .39 mm. You really have to see this to believe how tiny the hole is and that it is produced reliably in lots of two tons.

As with ball powder, this double base propellant is also surface coated or deterred to give better high velocity results. By deterring a neutral single perf, it now performs as a progressive geometry. So again, the performance goes beyond that available with deterred ball powder. Bofors uses a process for surface coating where the whole operation is done under water. The method allows very precise control of how deep the surface agent penetrates the grain.









12X

8. Grain Cross Section Picture

These cross sections show the high quality of the surface coating on both the inner and outer surface of the grain.

With this baseline understanding, the problem which now results with deterred ball powder is that during high temperature storage, such as several months at 145 degrees F, the excessive amount of nitroglycerin in the grain coupled with heat causes a migration of the surface deterrent further into the ball. The deterrent in the single perf will also migrate, but much less since less nitroglycerin is involved. Plus the nitroglycerin is evenly distributed so deterrent migration effects are minimized.

The unfortunate result with ball powder subjected to high temperature storage is that less deterrent is present in the location where it is most needed, at the outer surface of the ball powder grain. This is a worse condition for ball powder since to begin with, the nitroglycerin was unevenly absorbed, and greater amounts exist in the outer layers. When this ball powder cartridge is then fired, even at lower service temperatures, the grain reacts more violently and dangerous pressure spikes occur. Countries such as Sweden, France, and Germany have conducted testing over the years and have documented pressure increases of 15,000 psi in 7.62 ball powder cartridges, so stored. We have these reports on file. Pakistan and India have reported rifle explosions resulting from 7.62 ball powder cartridges exposed to long term hot storage. The United Kingdom does not even employ ball powder in its service ammunition for these reasons.

MECHANICAL PROPERTY DATA SHEET[1]

	TENSILE STRENGTH	YIELD STRENGTH	%ELONG.	HARDNESS
	PSI	PSI		RWC
		97% WA 18.5 G/CC		
SINTERED	134,921	90,424	15.1	30.3
SWAGED 15%	160,756	160,556	4.7	40.2
SWAGED 25%	174,853	174,460	2.4	42.4
		95% WA 18.0 G/CC		
SINTERED	132,119	85,356	24.3	28.7
SWAGED 15%	155,950	155,747	12.2	39.8
SWAGED 25%	169,494	169,080	7.9	41.2
		93% WA 17.6 G/CC		
SINTERED	133,805	87,519	29.0	28.4
SWAGED 15%	161,632	161,026	8.8	39.9
SWAGED 25%	171,626	170,406	7.5	40.6

1 Courtesy of Jim Bost, Teledyne Firth Sterling, Ordnance Division

9. Tungsten Alloy Mechanical Properties

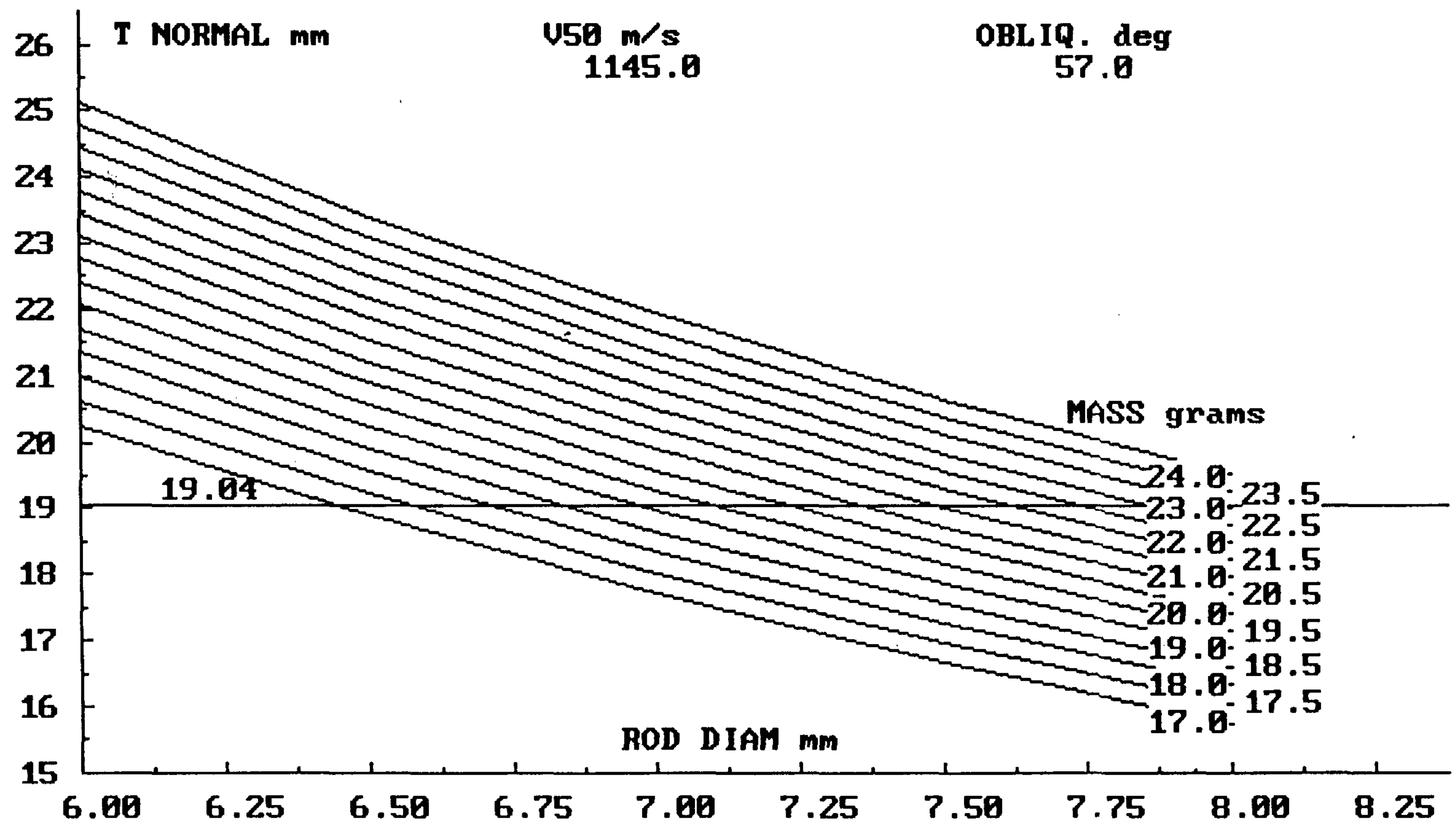
Teledyne Firth Sterling did a great job providing us with tungsten alloys to test, also as part of the iterative process of converging on the best projectile design.

We see three alloy densities, each at three levels of cold work: sintered or no cold work, 15% and 25% swaging or reduction in area (whatever term one prefers, they all mean the same thing). The result of cold working the alloy is that its strength and hardness increase significantly, but at a cost in ductility. Nevertheless, in order to safely launch the penetrator, at least 15% cold work is required, since the launch acceleration can reach 200,000 G's, which would snap the sintered alloy.

In addition, depending on target obliquity and hardness, the penetrator needs a critical level of strength and hardness to match. The target tested was high hard armor, which has a Rockwell C hardness of about 45. The specification is written as 500 Brinell hardness. If this target is perfectly vertical, the sintered alloy penetrator will easily penetrate it. However, as obliquity is introduced, the sintered alloy penetrator will bend and simply ricochet off the surface. You get a healthy respect for high hard armor doing these tests. Often, with the sintered alloy the surface of the armor is totally unblemished. There is simply a silvery wash where the projectile impacted. In disbelief, at first one feels that the target was missed, but since it was 2x2 feet in size and one foot from the muzzle, it clearly did not miss the target. High hard armor is very good.

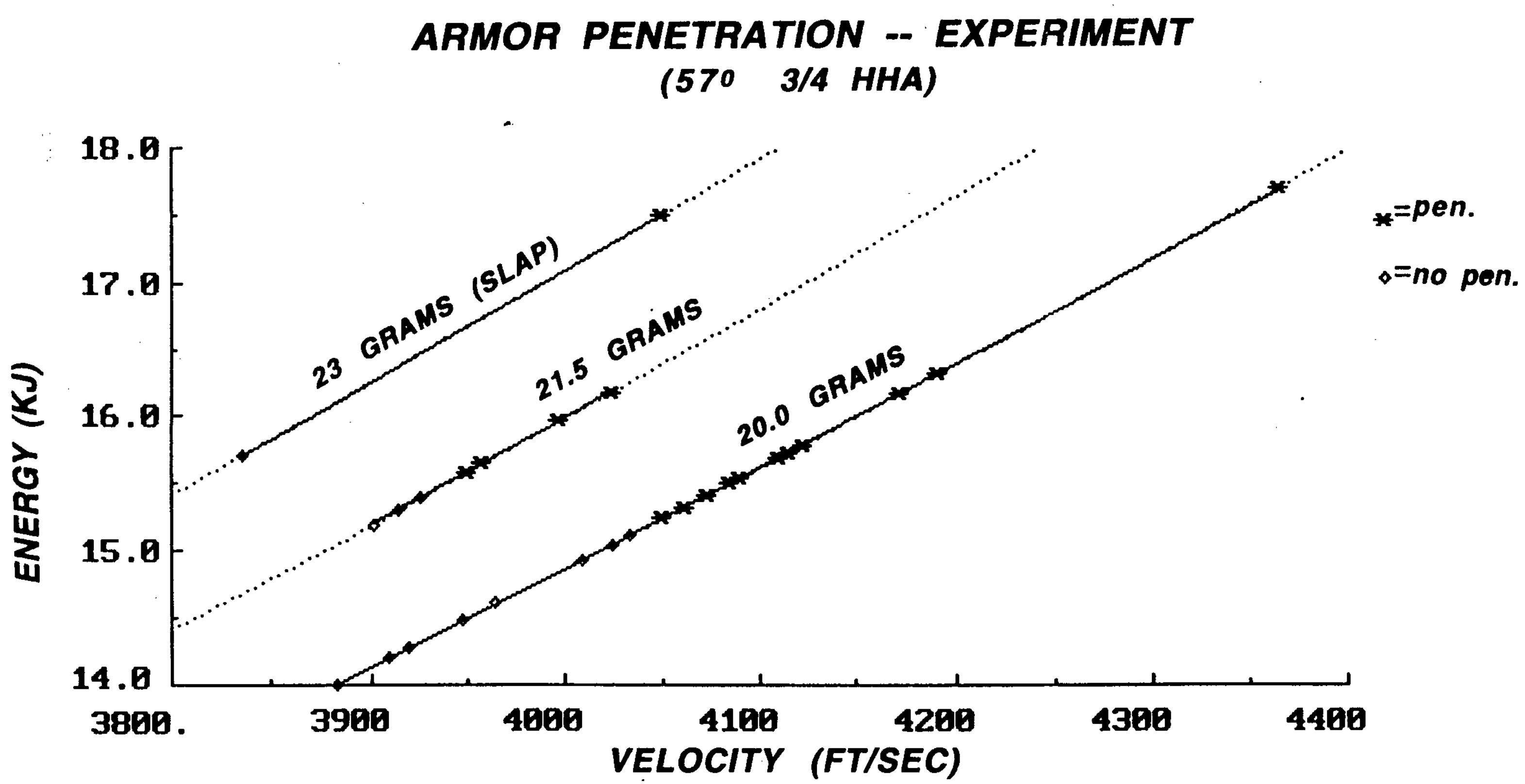
At obliquity, either the 15 or 25% swaged is sufficient to perforate high hard armor, but the penetrator must impact with very little yaw, since that may artificially increase the target obliquity and the round could still ricochet leaving a deep divot in the surface. The SLAP spec allows an 11 degree yaw angle, which is understandable with the sabot problems. We see less than 5 degrees in the first maximum yaw cycle for our design. This is exceptionally good and improves overall accuracy and target defeat capability.

ARMOR PENETRATION --THEORY
(57° 3/4 HHA)



10. 57 deg HHA Theory

As part of developing useful tradeoffs for sizing the penetrator and projectile, we conducted a literature review of penetrator models and found the Grabarek model to be the most intuitively complete. It accounts for the rod diameter, length, weight, strength and hardness; and the target thickness, hardness and obliquity for any given impact velocity. Here we see that one should be able to defeat the oblique high hard target with a lighter but more slender penetrator. So we set out to get data points to validate the theory, using our Teledyne tungsten alloys.



ARMOR PENETRATION -- EXPERIMENT
(57o 3/4 HHA)
ENERGY (KJ)
18.0
17.0
16.0
15.0
14.0
3800.
3900
4000
4100
4200
4300
4400
VELOCITY (FT/SEC)
23 GRAMS (SLAP)
21.5 GRAMS
20.0 GRAMS
*=pen.
◇=no pen.

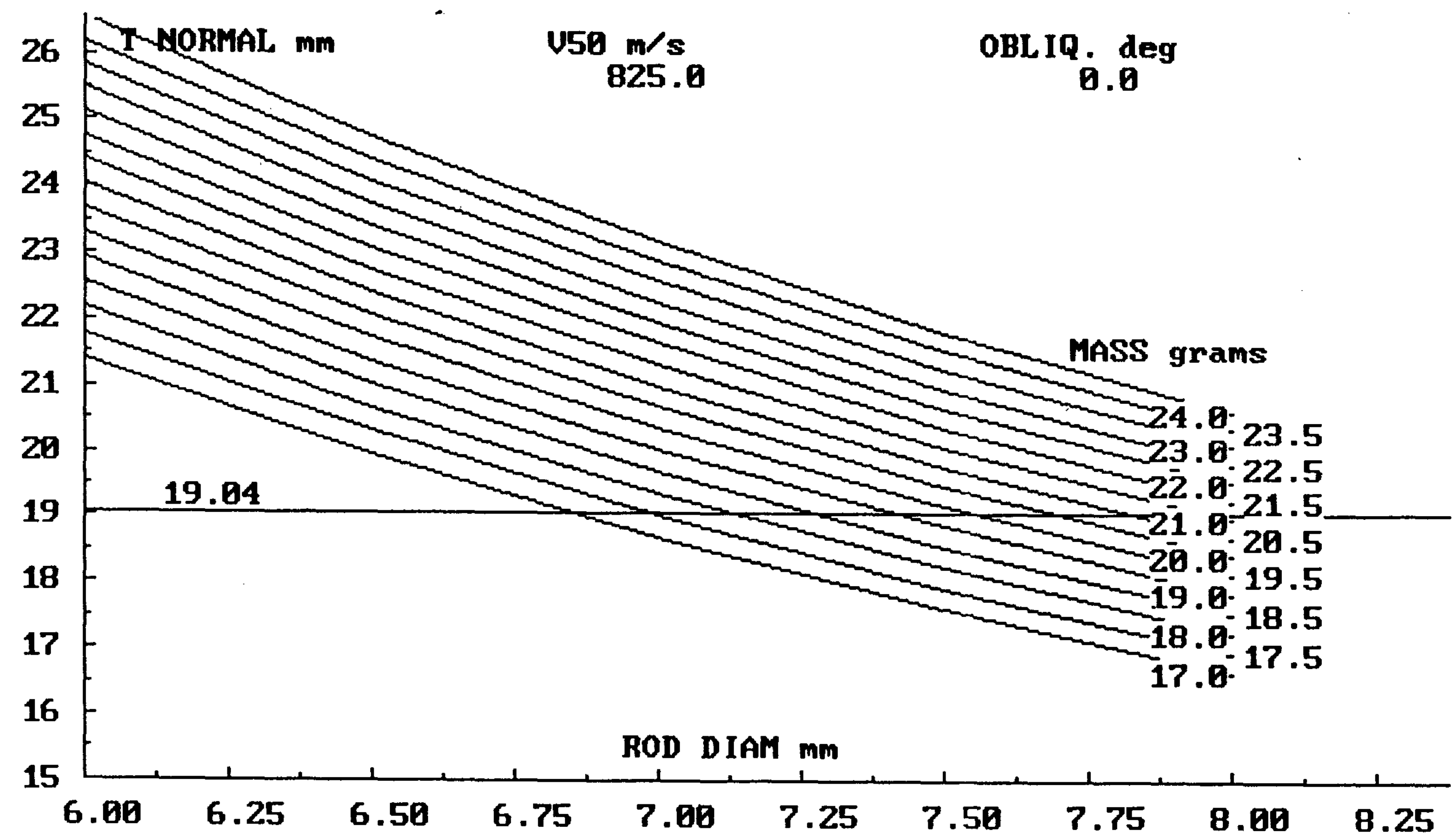
11. 57 deg HHA Experiment

So much for theory. After the smoke cleared, there was no correlation between rod diameter, hardness, density, mass and V50. All the data was scattered until I normalized it with respect to rod mass and impact kinetic energy. Then this trend appeared. What you see are equal penetrator mass lines and the change in kinetic energy depending on impact velocity. Except for the SLAP line, the others represent different rod diameters, densities, and either 15% or 25% swaged tungsten.

There appears to be a threshold kinetic energy below which the rod will not penetrate the target -- about 25 KJ for a 20 gram rod, 15.5 KJ for a 21.5 gram rod, and 16 KJ for a 23 gram rod. One sees that there is also a slight trend with respect to rod mass. Heavier rods need less impact velocity, but the overall kinetic energy is higher, so they are less energy efficient. Therefore, incrementally, it is better to have about 100 fps more velocity than 1 more gram in the penetrator. This information allowed us to select the best mass velocity relationship in the design.

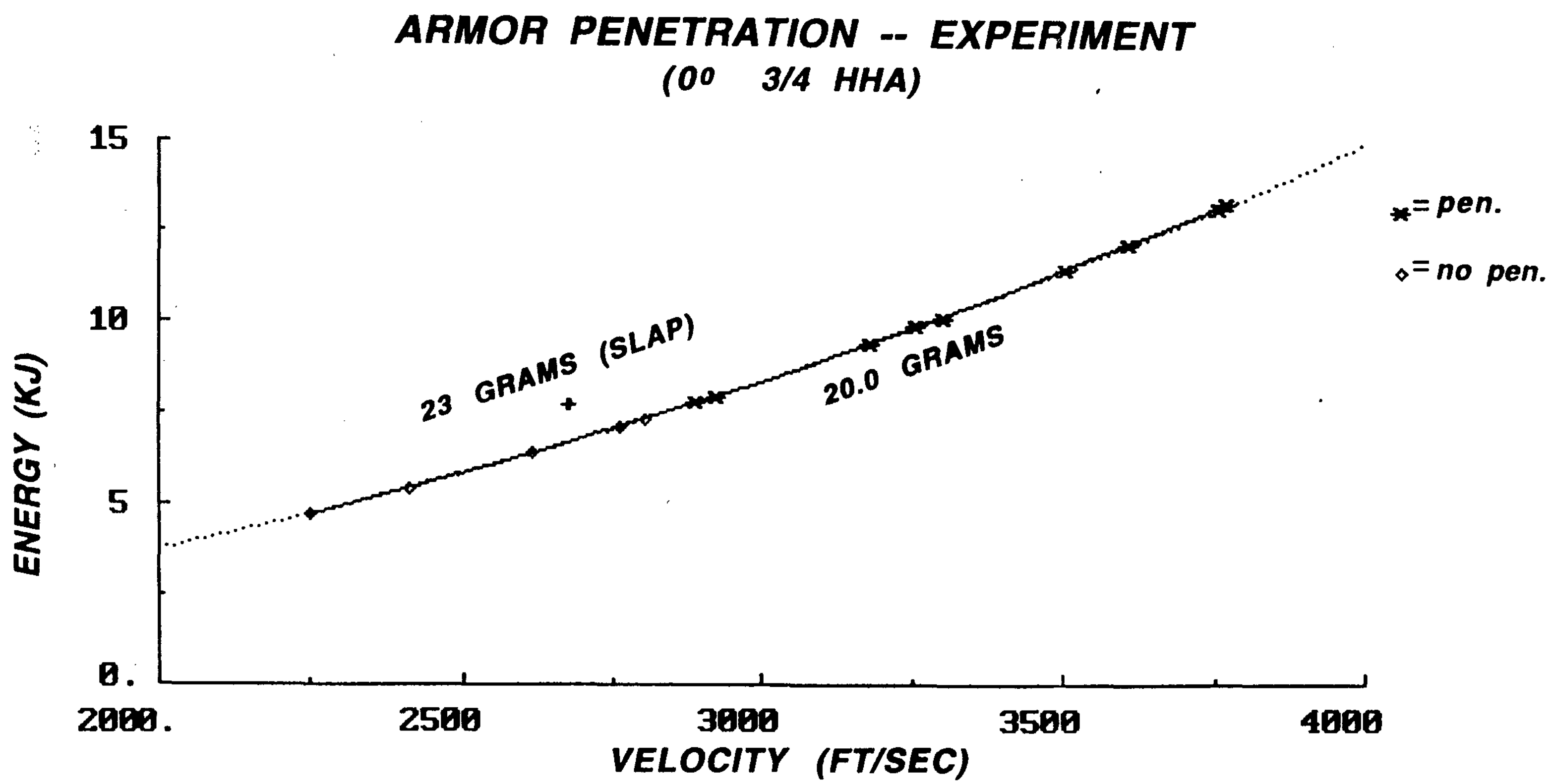
ARMOR PENETRATION --THEORY

(0° 3/4 HHA)



12. 0 deg HHA Theory

We ran the same theory against the vertical target. Same trends, but the velocity requirement is lower.

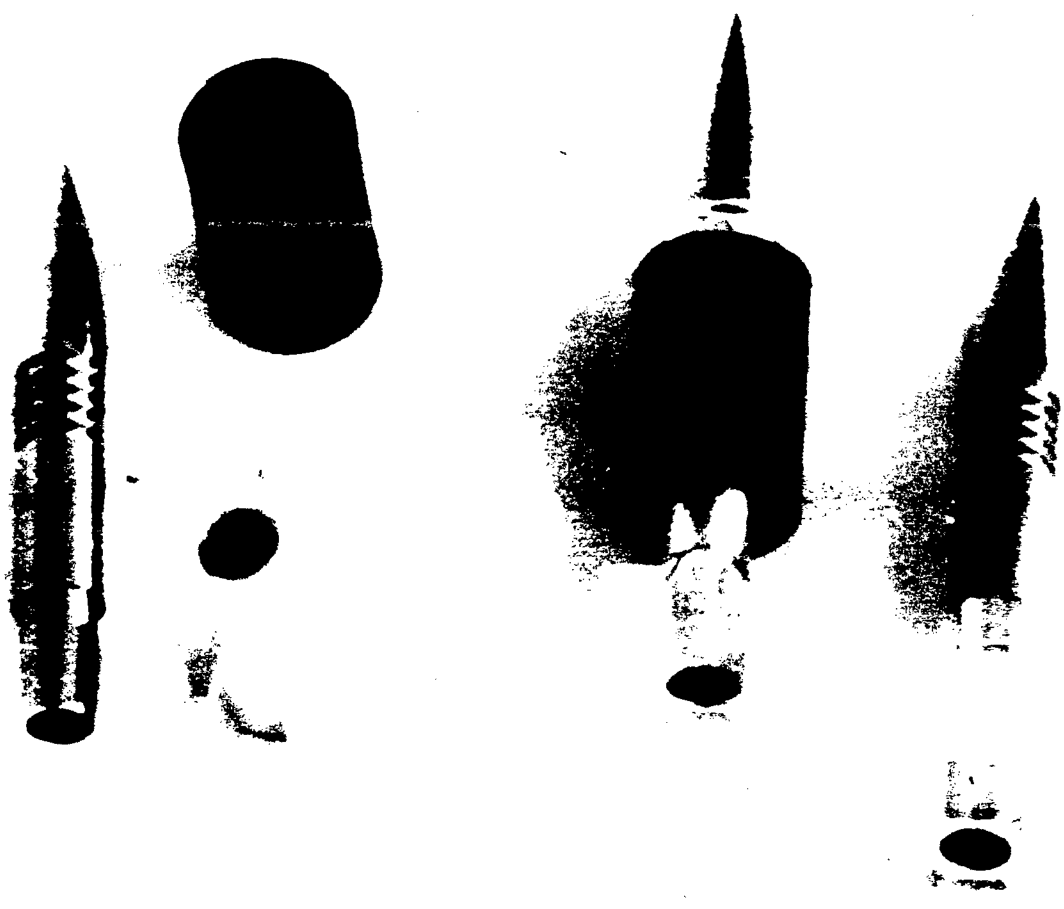


ARMOR PENETRATION -- EXPERIMENT
(0° 3/4 HHA)
ENERGY (KJ)
15
10
5
0.
2000.
2500
3000
3500
4000
VELOCITY (FT/SEC)
23 GRAMS (SLAP)
20.0 GRAMS
= pen.
= no pen.

13. 0 deg Experiment

It did not apply here either, and again the target is defeated based on a kinetic energy threshold, but significantly lower, around 7.5 KJ, about half the energy as against the oblique target.

This is where one sees the greatest improvements. At extended range, the more aerodynamically efficient design maintains its kinetic energy longer, giving the weapon greater overall usefulness in terms of armor penetration and accuracy against all types of maneuvering and stationary targets, be they helicopters, aircraft, APCs, trucks, personnel, etc. The technologies presented here also apply to systems ranging from .30 caliber to .60 caliber and beyond. Although I would not recommend employing a fin stabilized round in a .30 caliber systems. The size is really too small, and the current 7.62 SLAP tungsten carbide penetrator is adequate so long as one employs a more up-to-date and reliable sabot concept.



14. Component Picture

These are the major components of the final design. The penetrator employs a tracer cavity which does not reduce armor penetration performance. The tracer cavity may be filled with a suitable visible tracer, dim tracer, or invisible infrared pyrotechnic, depending on the application. SAA has developed tracer technology to support these uses.

The penetrator in this design weighs 22 grams, only 1 gram less than the SLAP penetrator. The fins weigh 1 gram, the segmented aluminum sabot weighs 1 gram. The balance of the projectile weight is in the plastic obturator. Total assembled weight is 26.5 grams, which is still 0.5 grams lighter than the 27 gram SLAP projectile. Therefore, additional design optimization could be performed to include the propellant characteristics. However, as mentioned, for an NDI design we consider performance to be adequately superior to anything on the market and the design is currently completed.

15. Linked Rounds and Target Plate

Here we show linked rounds and resulting HHA penetration. The large hole in the middle is the size of a quarter, and this particular shot even cracked the high hard armor plate, as can be seen. This section was cut from a larger plate for display purposes.